DISCHARGE CHARACTERISTICS OF A VERY LOW-POWER ARCJET

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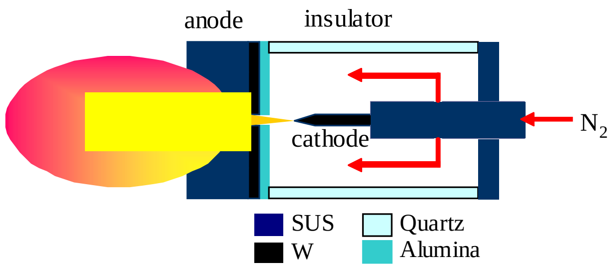
In this study, investigations on discharge characteristics, thrust performances and non-equilibrium characteristics of the interior plasma were carried out. As for a thruster used in this experiment, a clear quartz window was installed which enabled an observation of interior discharge characteristics, for cases of the constrictor diameter of 0.3mm and 0.5mm, and the anode-cathode distance of 0.5 (~ 4.0) mm. The length and maximum diameter of the body were 41mm and 17mm, respectively. With this thruster, discharge characteristics were investigated through the measurement of current-voltage variations and the observation of behaviors of an arc column with a color CCD video camera. Also, propulsive performance tests were conducted for various current and mass flow rate cases with a calibrated quartz cantilever thrust stand in which an optical lever was utilized to measure its displacement caused by the thruster in operation. Moreover, spectroscopic diagnostics on non-equilibrium characteristics from spontaneous emissions of the interior plasma of the thruster through the quartz window were carried out. It was observed that discharge voltages were almost constant with various discharge currents under very low-power operation. Also, it appeared that the emission of the interior discharge plasma was much weaker than the arc discharge in whole region including a cathode sheath region except near constrictor region where an intense emission (still weaker than arc) was seen. Plenum pressure inside the discharge chamber was about 20kPa, in typical cases. While in high-pressure cases, or higher current and mass flow rate cases, ~ 0.1MPa, an intense emission of the arc discharge was observed and a closure problem of constrictor became significant. From the propulsive tests, typical thrust was 1.5 ~ 2.0 mN, *I*sp: ~ 100 sec for input power of 1 ~ 5 watts and propellant (N_2) mass flow rate of 0.6 ~ 2 mg/sec. It was also found from the spectroscopic measurement of the spontaneous emission of the interior plasma that vibrational temperature of nitrogen molecule was about 2500 K, while its rotational temperature, about 1600K, at a constrictor inlet region. Although the plasma between electrodes was found to be in thermal non-equilibrium, the plasma, or the propellant, was heated and the thrust and specific impulse increased with input power.

INTRODUCION

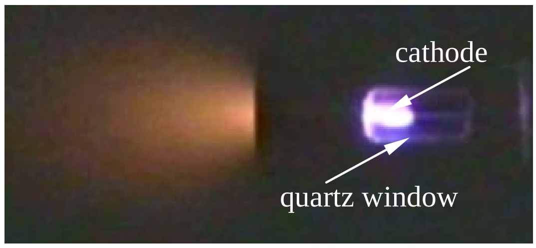
The current trend towards smaller spacecraft, which is not only mass limited but also power limited, has produced a strong interest in development of micropropulsion devices [1-3]. The significance in reducing launch masses has attracted growing interests in regard to reduction of mission costs and increase of launch rates. Although in the past, many very small spacecraft have lacked propulsion systems altogether, future microspacecraft will require significant propulsion capability in order to provide a high degree of maneuverability and capability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited microspacecraft missions[2]. Feasibility studies of microspacecrafts are currently under development for the mass less than 100 kg with an available power level for propulsion of less than 100 watts [2-20]. Various potential propulsion systems for microspacecraft applications, such as ion thrusters [4-7], field emission thrusters [8, 9], PPT [10, 11], vaporizing liquid thrusters [12, 13], resistojets [14-16], microwave arcjets [17], pulsed arcjets [18, 19], etc., have been proposed and are under significant development for primary and attitude control applications

As for low power DC arcjets operational at power levels down to about 300 watts, several investigations have been conducted on their use for north-south stationkeeping (NSSK) on geosynchronous satellites [21-32]. However, there has been little focus on the study of DC arcjets operational at very low power levels, i.e., less than 100 watts [20], for microspacecraft propulsion devices, relating not only to the thrust performance but to fundamentals of the very low power DC discharges [33] as well. The structural simplicity of an arcjet may be favorable for both size and mass reduction of the thruster; also, further reduction of the input electrical power, to less than 100 watts for example, may be effective for reducing the mass of the power supplies. In addition, very low power operation of arcjets, especially at reduced specific power levels with lower temperature of the propellant which is heated through the discharge, will elongate the life of electrodes and reduce the electrode losses and frozen flow losses, resulting in higher thrust efficiency [34]. Although the specific impulse achievable during operation will be reduced at low specific power levels, it will be recovered to some extent through the achievement of loss reduction.

The objective of this study is to investigate the fundamentals of discharge characteristics and the performance of very low power DC arcjets with electrical input power levels ranging from approximately 1 ~ 10 watts in order to ascertain the effective operational condition which possibly results in higher thrust performance. In this study, the conditions for stable operation and diagnostics of an internal flow of the arcjets, temperature measurements of plasma in a discharge chamber were conducted. Also, thrust performance, such as thrust, specific impulse and thrust efficiency of a very low-power arcjet, was evaluated.



(a) Schematic of an arcjet thruster.



(b) Photo of an arcjet thruster in operation.

Fig.1 Schematics of an arcjet thruster.

EXPERIMENTAL

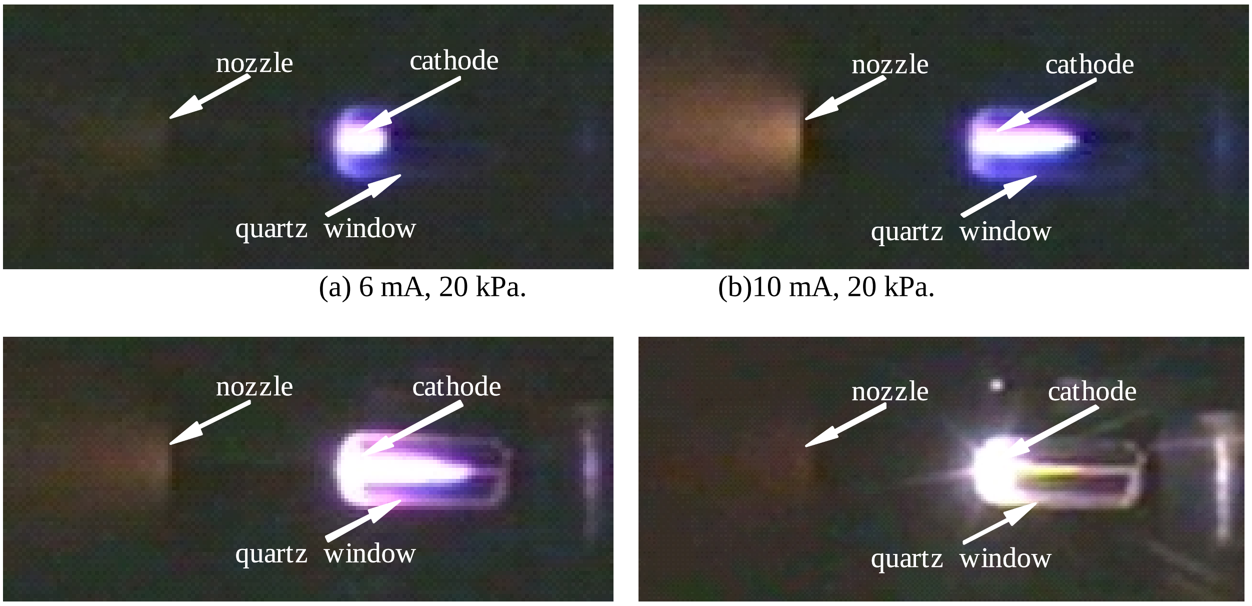
A cross-sectional schematic of an arcjet thruster used in this study is shown in Fig.1(a). In general, an arcjet nozzle consists of a metallic material, and serves a dual function as an anode and an arc column constrictor, except for a divergent section. In this study, a ceramic material with low heat conductivity for a convergent section and the following part of the constrictor in a nozzle was used to reduce electrode losses.

Sizes of the thruster are 41 mm in length, 17 mm in diameter (maximum), constrictor diameter of 0.3 mm (or 0.5 mm), and anode-cathode gap of 0.5 mm. A photo of the thruster is given in Fig.1(b). The inner thruster body consists of a clear-quartz tube to diagnose internal behaviors of the discharging plasma measuring spontaneous emissions from the plasma with the color CCD camera and the multichannel spectrum analyzer. For the ceramic material, the alumina (Al_2O_3) was used for a part of the constrictor to allow the arc column to penetrate further downstream of the constrictor, or to maintain the high-voltage mode discharges, and possibly reduce the electrode losses. The cathode used in the tests was made from a tungsten rod 0.5 mm in diameter with a conical tip angle of 15 degrees. Nitrogen gas was used as a propellant, and the feed pressure was measured upstream of the plenum. In this study, in order to establish stable discharges at very low current levels ranging from 1 ~ 10 mA, a high-voltage power supply with high ballast resistance was used.

A thrust performance test was conducted in a vacuum vessel. A calibrated cantilever-type thrust stand consisting of quartz plates was used for the measurement. The specific impulse: *I*sp and the thrust efficiency: η are calculated using the values of T : total thrust, T_c : thrust of cold gas jet, m: mass flow rate, and *P*in:

electrical input power [30].

Spectroscopic measurements were also conducted to evaluate the effects of variations in the mass flow rate and discharge current on heavy particle, or molecular nitrogen, temperature of the heated propellant. In order to evaluate the gas temperature, the wavelength (300 ~ 800 nm) and spectrum intensity of the spontaneous emission of the gas on a central axis of the discharge chamber were measured using a multichannel spectrum analyzer. Based on spectroscopic theories [35], the spontaneous emission spectrum resulting from electronic transitions of nitrogen molecules (1st Positive System, $B^3\Pi_g$ $A^3\Sigma_u^+$) [36] was calculated for a given set of conditions. Here, the parameters assumed for computing each theoretical spectrum were the number density of the gas, the vibrational temperature (Tvib) and the rotational temperature (Trot). The temperatures (Tvib and Trot) of the gas were found by selecting a set of parameters which makes the calculated spectrum fit well to the measured spectrum [33].



(a) 6 mA, 20 kPa. (b)10 mA, 20 kPa.

(c) 12 mA, 20 kPa. (d)13 mA, 20 kPa.

Fig.2 Photos of discharging plasmas in thruster.

RESULTS AND DISCUSSION

Behaviors of Discharge Plasma

Images of discharging plasmas in a very low-power arcjet taken by a color CCD camera (30 frames/sec, 30 msec/frame) are shown in Figs.2(a)~(d). When the discharge current is low, (a) 6 mA, a stable violet emission forming a sheath around a cathode tip can be seen. As the current rises, (b) 10 mA and (c) 12 mA, increasing its intensity, the region of the violet emission forming the sheath extends along the cathode from the tip. In a much higher current case, (d) 13 mA, the emission is concentrated into the cathode tip increasing its intensity significantly and heating the tip, and then the discharge transition occurs into a hot cathode arc discharge. While this arc transition, it is observed that the discharge becomes significantly unstable. Plenum pressure inside the discharge chamber is about 20kPa, in typical cases. While in high-pressure cases, or higher current and mass flow rate cases, ~ 0.1MPa, and a closure problem of constrictor became significant.

In this study, lower current range (~10 mA), within which discharge transition into the arc does not occur, is selected to keep a stable discharge. Since the emission intensity in this case is much lower than the arc case (d), the discharge is different from a normal arc discharge but probably a low-pressure arc or a glow discharge.

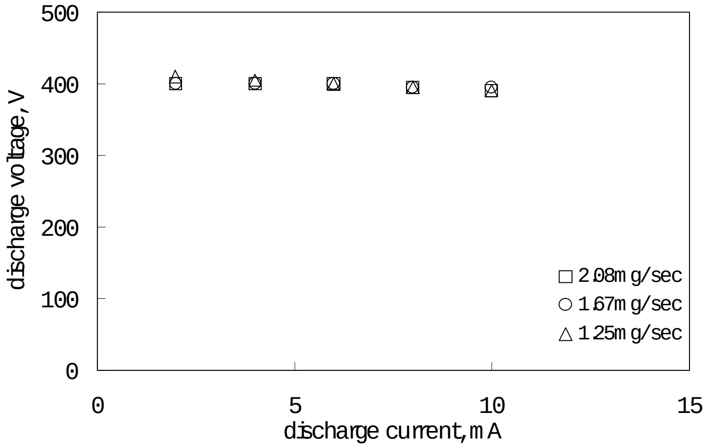


Fig.3 Discharge current-voltage characteristics.

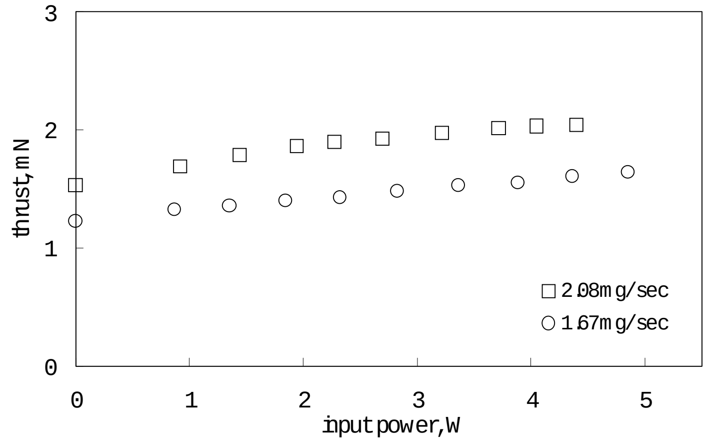


Fig.4 Input power vs thrust.

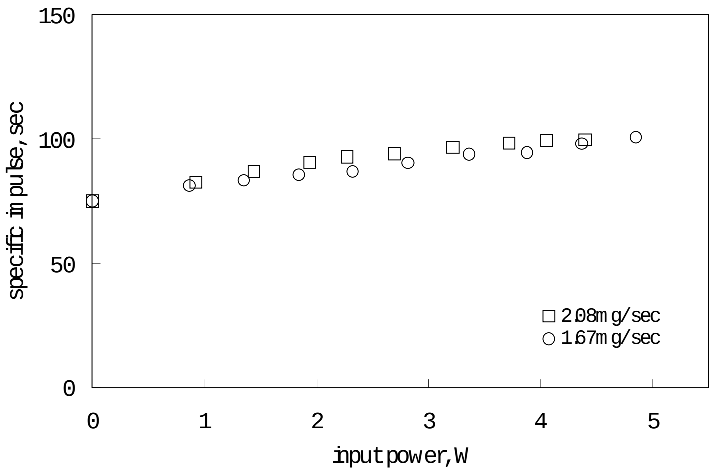


Fig.5 Input power vs specific impulse.

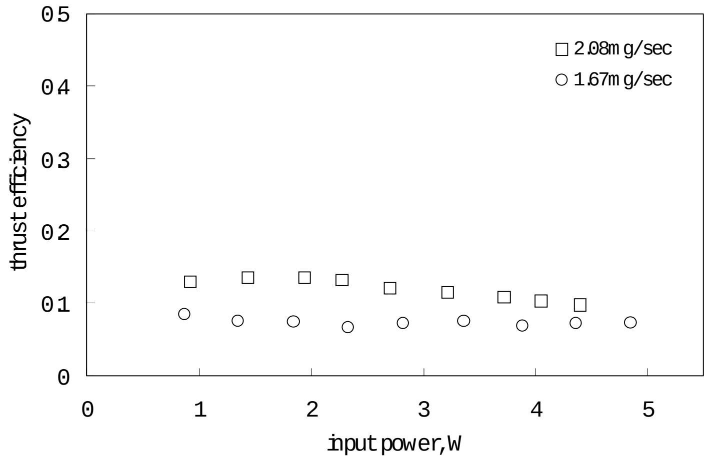


Fig.6 Input power vs thrust efficiency.

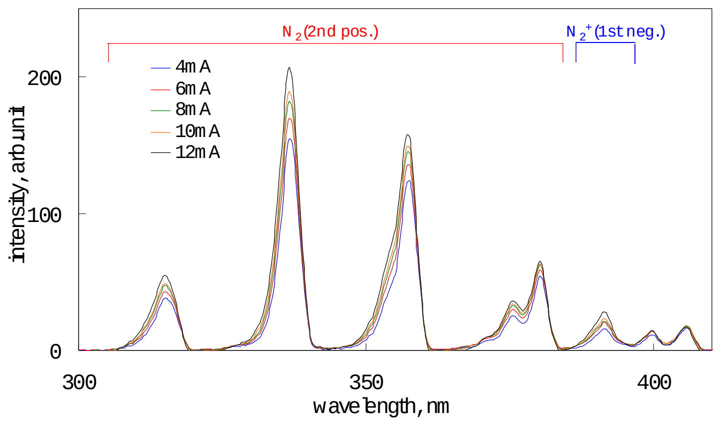


Fig.7 Typical spontaneous emission spectra from interior plasma of arcjet.

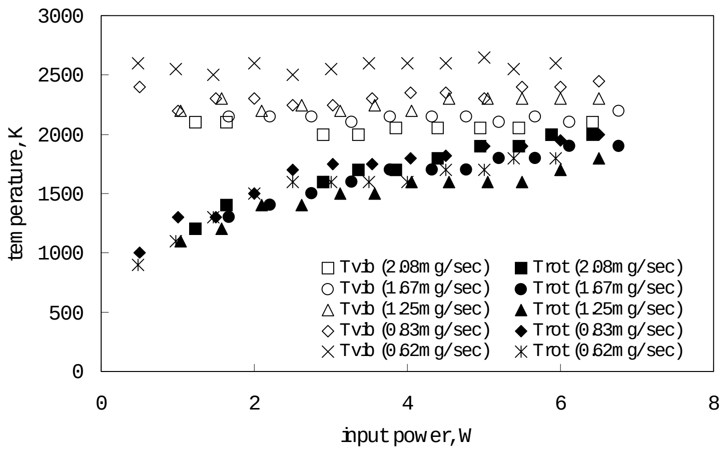


Fig.8 Input power vs heavy particle temperature.

Discharge Characteristics of Arcjet

The discharge current-voltage characteristics are shown in Fig.3. It is observed that the discharge voltage for all cases is almost constant or gradually increases as the current decreases over the range 1 ~ 10 mA. Although this tendency is not typical electric characteristics of an arc discharge, it must be emphasized that the stable DC discharge is established even under this very low current level [20].

It was observed that the plenum pressure increases from 20 to 36 kPa with increasing the arc current. The pressure increases with the arc current probably due to the flow blockage induced by a bigger arc column with higher arc current [6]. This results in the decrease of the effective diameter of the throat due to the flow blockage by an arc column and the increase of the plenum pressure as the arc column penetrates further into the constrictor. It is shown that the discharge type under very low-current range (< 10 mA) in the low plenum pressure level is different from a normal arc discharge but probably a low-pressure arc discharge or a glow discharge.

Effects of arcjet input power of less than 5 W on the thrust are shown in Fig.4 for the propellant mass flow rates 1.67mg/sec and 2.08 mg/sec. Fig.5 shows the plots of specific impulse versus arcjet input power (~ 5 W). It must be noted that the thrust and specific impulse show linear increases even with very low power levels of ~ 5 W. For a higher mass flow rate case, slightly lager specific impulse is obtained. Values of the specific impulse in these cases are much lower than expected probably due to the significant radiative heat loss through a quartz window.

Fig.6 shows the relationship between input power and thrust efficiency. It is shown that higher thrust efficiency is obtained in a higher mass flow rate case, and the thrust efficiency gradually decreases with input power. As mentioned above, because of the excessive radiative heat loss from the quartz window constituting the main body of the arcjet, the values of measured efficiency must be lowered to some extent. Also, considering very high voltages between the electrodes during the operation, near electrode voltage drops, which constitute a local heat loss of the electrodes, may be large [31].

Examples of spontaneous emission spectra of interior plasmas of the arcjet for various discharge currents are shown in Fig.7. From the figure, the spectra of the interior plasmas are mainly in UV region, i.e., second positive system of N_2 and first negative system of N_2^+. Moreover, the intensity of the spectra in this wavelength region rises with increasing the discharge current and with decreasing the mass flow rate, in which cases radiative energy, or loss, from the plasma through the quartz window also increases.

Plots of heavy particle temperatures of the plasma in a discharge chamber versus arcjet input power, for various mass flow rate cases are shown in Fig.8. Under the experimental conditions, it was observed that the rotational temperature (Trot) and the vibrational temperature (Tvib) of the nitrogen gas in the discharge chamber estimated through the spectroscopic measurements are found in nonequilibrium in most cases. In Fig.8, it is shown that the vibrational temperature is almost constant with increasing arcjet input power for each mass flow case but significantly rises with decreasing the mass flow rate. On the other hand, the rotational temperature is almost constant with the mass flow rate but significantly increases with the current. Also it can be seen that the difference between vibrational temperature and rotational temperature, or the degree of thermal nonequilibration, becomes smaller with higher current and higher mass flow cases. For example, in a higher mass flow case with higher input power (e.g. 2.08 mg/sec, 7 W), Tvib ~ Trot ~ 2,000 K, and almost in thermal equilibrium. While in a lower mass flow case with lower input power (e.g. 0.62 mg/sec, 1 W), Tvib ~ 2,500 K, Trot ~ 1,200 K, and in higher thermal nonequilibrium.

From these results an improvement of thrust efficiency with higher mass flow rate cases in Fig.6 is probably due to higher thermal equilibrium states established in those cases as shown in Fig.8. Although an increase of the degree of thermal equilibration is also obtained with higher current cases, improvements of the thrust efficiency are insignificant in Fig.6. From Fig.7, this is probably due to the increase of the radiative loss occurring at the same time.

CONCLUSIONS

Investigations on discharge characteristics, thrust performances and non-equilibrium characteristics of the interior plasma were carried out. As for a thruster used in this experiment, a clear quartz window was installed which enabled an observation of interior discharge characteristics, for cases of the constrictor diameter of 0.3mm and 0.5mm, and the anode-cathode distance of 0.5 (~ 4.0) mm. The length and maximum diameter of the body were 41mm and 17mm, respectively. With this thruster, discharge characteristics were investigated through the measurement of current-voltage variations and the observation of behaviors of an arc column with a color CCD video camera. Also, propulsive performance tests were conducted for various current and mass flow rate cases with a calibrated quartz cantilever thrust stand in which an optical lever was utilized to measure its displacement caused by the thruster in operation. Moreover, spectroscopic diagnostics on non-equilibrium characteristics from spontaneous emissions of the interior plasma of the thruster through the quartz window were carried out. It was observed that discharge voltages were almost constant with various discharge currents under very low-power operation. Also, it appeared that the emission of the interior discharge plasma was much weaker than the arc discharge in whole region including a cathode sheath region except near constrictor region where an intense emission (still weaker than arc) was seen. Plenum pressure inside the discharge chamber was about 20kPa, in typical cases. While in high-pressure cases, or higher current and mass flow rate cases, ~ 0.1MPa, an intense emission of the arc discharge was observed and a closure problem of constrictor became significant. From the propulsive tests, typical thrust was 1.5 ~ 2.0 mN, *I*sp: ~ 100 sec for input power of 1 ~ 5 watts and propellant (N_2) mass flow rate of 0.6 ~ 2 mg/sec. It was also found from the spectroscopic measurement of the spontaneous emission of the interior plasma that vibrational temperature of nitrogen molecule was about 2500 K, while its rotational temperature, about 1600K, at a constrictor inlet region. Although the plasma between electrodes was found to be in thermal non-equilibrium, the plasma, or the propellant, was heated and the thrust and specific impulse increased with input power.

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